TIME AND FREQUENCY ACTIVITIES AT THE NASA JET PROPULSION LABORATORY

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Abstract

The Jet Propulsion Laboratory, NASA's lead center for frequency and timing, develops and implements state-of-the-art atomic frequency standards, clocks, dielectric resonators, stabilized photonic links, and low-noise test and measurement capabilities in support of demanding applications for spaceflight and the NASA Deep Space Network (DSN). When implemented into the DSN Frequency and Timing Subsystem (FTS), these technologies provide precise and stable phase, frequency, and time references for NASA's deep space communication, tracking, navigation, and radio science activities. A brief overview of JPL time and frequency research, development, implementation, and operation activities is presented with a focus on recent frequency and timing advances in the NASA DSN and the JPL Frequency Standards Test Laboratory (FSTL).

INTRODUCTION

The NASA Jet Propulsion Laboratory (JPL), a federally funded research center, is located in the foothills of Pasadena, California, and managed by the California Institute of Technology. For over 40 years, the laboratory has led unmanned space exploration throughout the solar system. In this effort, JPL operates the NASA Deep Space Network (DSN), with three major Deep Space Communication Complexes (DSCC) located near Madrid, Spain; Canberra, Australia; and Goldstone, California, USA.

The laboratory employs ~5,000 engineers and scientists organized under several directorates and divisions. The largest technical division is the Communication, Tracking, & Radar Division, with nearly 700 employees organized under six sections that perform a broad range of systems engineering, research & development, implementation, and operations activities. Frequency and timing activities are concentrated in the Tracking Systems and Applications Section and the Frequency and Timing Advanced Instrument Development Group. The staff is a complementary mix of technologists, engineers, physicists, and mathematicians. A mastery of systems engineering and driving requirements helps motivate and filter appropriate technologies. A balance of research and engineering is needed to advance developments

[1]This work was performed by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Report Documentation Page

Report Documentation Page	Form Approved OMB No. 0704-0188

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1. REPORT DATE **NOV 2007**	2. REPORT TYPE	3. DATES COVERED **00-00-2007 to 00-00-2007**
4. TITLE AND SUBTITLE **Time and Frequency Activities at the NASA Jet Propulsion Laboratory**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **California Institute of Technology,Jet Propulsion Laboratory,Pasadena,CA,91109**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S)
		11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
39th Annual Precise Time and Time Interval (PTTI) Meeting, 26-29 Nov 2007, Long Beach, CA

14. ABSTRACT
The Jet Propulsion Laboratory, NASA?s lead center for frequency and timing, develops and implements state-of-the-art atomic frequency standards, clocks, dielectric resonators, stabilized photonic links, and low-noise test and measurement capabilities in support of demanding applications for spaceflight and the NASA Deep Space Network (DSN). When implemented into the DSN Frequency and Timing Subsystem (FTS), these technologies provide precise and stable phase, frequency, and time references for NASA?s deep space communication, tracking, navigation, and radio science activities. A brief overview of JPL time and frequency research, development, implementation, and operation activities is presented with a focus on recent frequency and timing advances in the NASA DSN and the JPL Frequency Standards Test Laboratory (FSTL).

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**16**	

and bring state-of-the-art capabilities to the operational environment. The Tracking Systems and Applications Section is also home to nine groups specializing in synergistic topics. In addition to advanced frequency and timing development, they also include radiometric tracking, space geodesy, GPS satellite systems, astronomical measurements, and gravity sensing instruments. Other related technical fields are also organized in other Sections, which include a broad range of expertise in radar and communications.

NASA currently has nearly 60 missions in flight exploring the solar system. Within NASA, JPL-led missions are strongly associated with robotic deep space exploration and operation of the Deep Space Network (DSN). JPL presently has missions exploring the edge of the solar system (Voyager), in orbit around Saturn (Cassini), and in transit to/orbiting/roving the surface at Mars (PHOENIX/MRO/MER). New challenging missions are also in development to return to Jupiter (JUNO) and perform sensitive gravity mappings of the moon (GRAIL). All of these missions rely on the highly specialized spacecraft-tracking capabilities of the DSN, which has evolved over four decades and currently consists of over 20 large-aperture antennas (34-70 meter diameter), and numerous specialized communication, navigation, and radio science capabilities. Each tracking complex and antenna is supported by significant low-noise, high- stability frequency and timing standards, signal transport, and measurement capabilities collectively referred to as the DSN Frequency and Timing Subsystem (FTS). The DSN FTS aims for state-of-the-art stability performance in a remote operational environment, but is also required to be extremely reliable. These extreme and often opposing requirements have historically driven the technology focus and selected development paths for frequency and timing activities at JPL.

DSN FREQUENCY AND TIMING SUBSYSTEM (FTS)

OVERVIEW

Without high-performance and very reliable frequency and timing sources and references, the DSN would not function and accurate spacecraft navigation would not be possible. The DSN operates FTS capabilities at each DSCC, and a specialized evaluation and test facility in Pasadena, California. Each DSCC may track multiple spacecraft by simultaneously operating several antennas distributed over tens of kilometers. Deep space exploration and navigation accuracy is highly dependent on specialized frequency and timing metrology **[1]**. All communication and tracking uplink signals originate from very stable, accurate, and precise frequency standards/clocks, and all received spacecraft downlink signals are referenced (for down-conversion, demodulation, or calibration) against these same high performance standards. The success of ranging, Doppler tracking, and VLBI-based navigation methods such as Delta Differential One-way Range (DDOR) directly depends on the calibration and frequency, time, and phase stability of the DSN Frequency and Timing Subsystem (FTS).

In addition to supporting deep space navigation activities, the FTS must also provide reliable reference signals for communication, telemetry, and demanding radio-science activities. To meet these multiple needs, the DSN FTS provides a common frequency and timing reference signal at each DSCC originating from a single, centrally located frequency standard and master clock. All reference signals distributed across an entire DSCC are coherent and synchronized.

The operational DSN FTS is schematically shown in Figure 1 and requires the following elements:

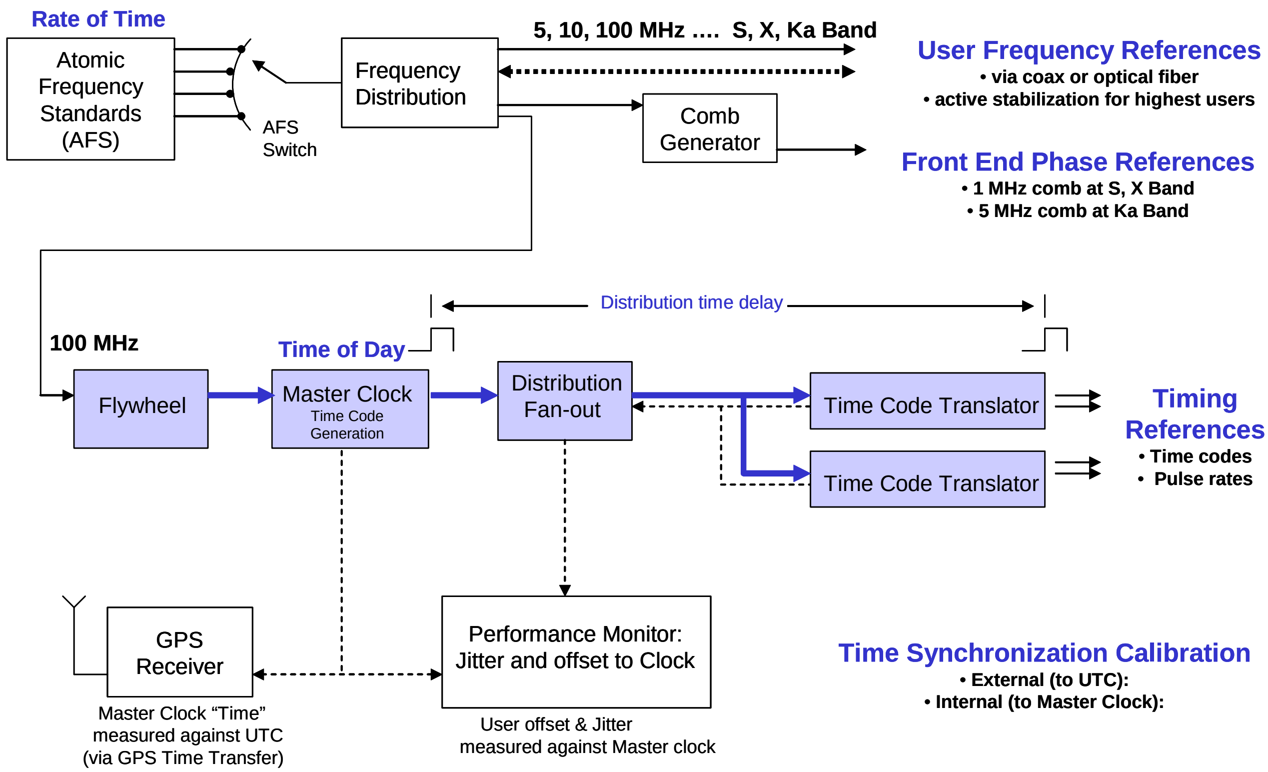

Figure 1. Schematic view of the DSN Frequency and Timing Subsystem (FTS).

1. Calibrated and Ultra-Stable Frequency Standards and Time References:
   - Central atomic frequency standard (AFS) & phase noise clean-up oscillator
   - Central clock for generating "time of day" and timing pulses

2. Ultra-Stable Frequency and Timing Distribution Links throughout each DSCC (to 30 km):
   - Frequency-standard selection/switching, coherent frequency synthesis, and distribution
   - Phase-stable frequency reference distribution over fiber-optic cables
   - Stable phase calibration tones at S, X, and Ka bands
   - Synchronized distribution of timing references (time of day and rate pulses) over fiber-optic cables

3. Calibrated User Reference Signals and Verified Performance:
   - Internal frequency and phase stability of standards and distribution links
   - Internal time synchronization offset & jitter
   - External offset calibration between the DSCCs and UTC via GPS time transfer

4. Monitor and Control Functions:
   - System operability, redundancy, and reliability management
   - Frequency and time calibration (external and internal) and leap-second management
   - Stability performance optimization and maintenance.

For the last decade, the JPL Frequency and Timing Advanced Instrument Development Group has led

new advances in NASA DSN frequency and timing. In 1998, many of the frequency and timing subsystems had insufficient capacity to handle a growing DSN and had become antiquated. At that time, a new system approach for increased operability was implemented. This resulted in a flexible and cost-effective monitor and control methodology and the development of needed time and frequency performance measurement and validation tools **[2-5]**. Also, at that time, a long-term plan to methodically revitalize and upgrade several major subsystems of the FTS was initiated, which is ongoing today.

FREQUENCY AND TIME STANDARDS

The frequency standards and their stability performance are critical to operation of the DSN. Each DSCC operates a complement of two hydrogen masers and two commercial cesium-beam standards. The H-masers together with a clean-up oscillator serve as the ultra-low phase noise reference source and provide the long-term stability to drive a locally maintained timescale. The DSN H-masers provide their best stability between 1,000 and 40,000 seconds, which corresponds well with needed stability for horizon-to-horizon tracking (~12 hours maximum) or the round-trip light time to spacecraft exploring the outer solar system.

Typical DSN frequency standard stability is summarized in Figure 2. Typically, an H-maser is cleaned up with the best available quartz oscillator for good short-term stability and phase noise. When available, a Cryogenic Sapphire Oscillator (CSO) may be used for phase noise cleanup on special occasions, such as for radio science activities with the Cassini spacecraft currently in orbit around Saturn **[6-9]**. Also shown in Figure 2 is the representative performance of a commercial cesium standard which is available for emergency backup. In event of failure of both DSCC hydrogen masers, the cesium-beam standard backup would support basic communication and telemetry with the tracked spacecraft, but would not be sufficiently stable to support most radio science activities. It has been well over 20 years since the DSN has operated even briefly in such a fall-back position.

For successful spacecraft navigation, the location of each DSCC and each antenna must be known to high accuracy; and the frequency and timing offsets between each FTS user known to high precision. At each DSCC, a master clock generates a local timescale, and timing offsets are calibrated and monitored against UTC (NIST) using GPS common-view satellite time and frequency transfer. The DSN FTS provides internal frequency, time, and phase stability within each DSCC 10 to 100 times more stable than what can be provided or measured via GPS-satellite time transfer (see Figure 2). The presently implemented GPS time transfer capability limits the number of calibration measurements to a few per day, and the precision is limited due to noise in the GPS time transfer process. To determine the DSCC clock offset to UTC (and, therefore, to UT) navigation solutions must currently interpolate between noisy GPS time calibration measurements. Only after more than a week of averaging time is the long-term stability of the local DSCC timescale compared to UTC apparent.

As each DSCC site consists of multiple antennas distributed over tens of kilometers, distribution timing delays and phase instabilities within each DSCC must also be carefully accounted for. Great care is taken to implement fiber-optic-based distribution systems and electronics with very low thermal and mechanical sensitivities **[10]**. For the most critical systems, distribution-related phase instabilities are monitored and actively compensated for **[8-11]**.

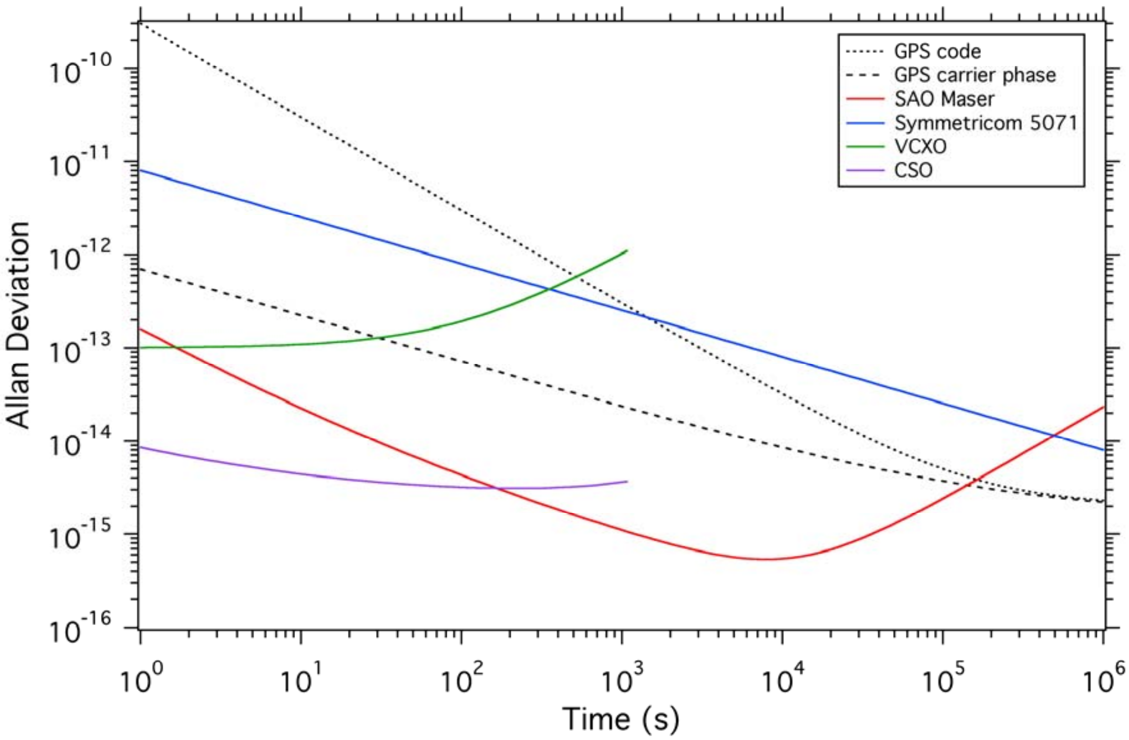

Figure 2. DSN FTS frequency standard performance. The dashed lines represent limits of GPS time transfer.

Recently, a major system upgrade to replace the central DSN FTS master clock and timing distribution system has been completed **[12,13]**. In 2005, a new system (Figure 3) replaced a complicated and obsolete timing subsystem and significantly reduced risk to DSN operations. The new clock and photonic-based distribution required a custom system design to meet the unique needs of the DSN. High performance, modularity, redundancy, and system operability were all key drivers. System component non-recurring engineering and hardware production were carried out with the participation of an industrial timing vendor. This strategy yielded the needed high-performance system design with a commercially sustainable product to support DSN operations for many years. The master clock and distribution system (Figures 1 and 3) provides internal synchronization across each DSCC (up to 30 km) to better than 10 ns and a timing jitter to all distributed users below 40 ps. A highly modular/redundant system design and unique dual-flywheel concept have resulted in an extremely flexible and reliable subsystem **[12,13]**.

Figure 3. The DSN Master Clock and Timing Distribution System **[12,13]**.

THE JPL FREQUENCY STANDARDS TEST LABORATORY (FSTL)

The success of the DSN FTS is coupled to and relies on a unique evaluation and test capability at JPL, built in 1985, and referred to as the JPL Frequency Standards Test Laboratory (FSTL). This facility, shown in Figure 4, provides a highly regulated ambient environment for characterizing the stability of the most stable frequency standards, clocks, distribution, and measurement hardware. The facility houses three large environmental test chambers with a high degree of thermal (15-35°C), pressure (±0.9 psi), and humidity (11-90%) control. Magnetic and vibration testing are also available in the laboratory. The entire laboratory has uninterruptible power systems with generator backup. Many channels of high-performance, low noise floor testing are available including capabilities to measure Allan and time variance, precision voltage level and thermocouple monitoring, and phase noise testing. In addition to a very flexible measurement system still operating on an obsolete HP-1000 computer, the FSTL also operates a newer seven-channel Frequency Standards Stability Analyzer **[4,5]**. This latter system inputs 100 MHz signals and compares them via a dual mixer method to a common reference offset at 100 Hz **[3]**. A recent addition of a low-noise commercial synthesizer on the front end of the FSSA has extended its measurement range to nearly 70 GHz. The FSSA noise floor is shown in Figure 5 **[5]**.

Figure 4. The JPL Frequency Standards Test Laboratory.

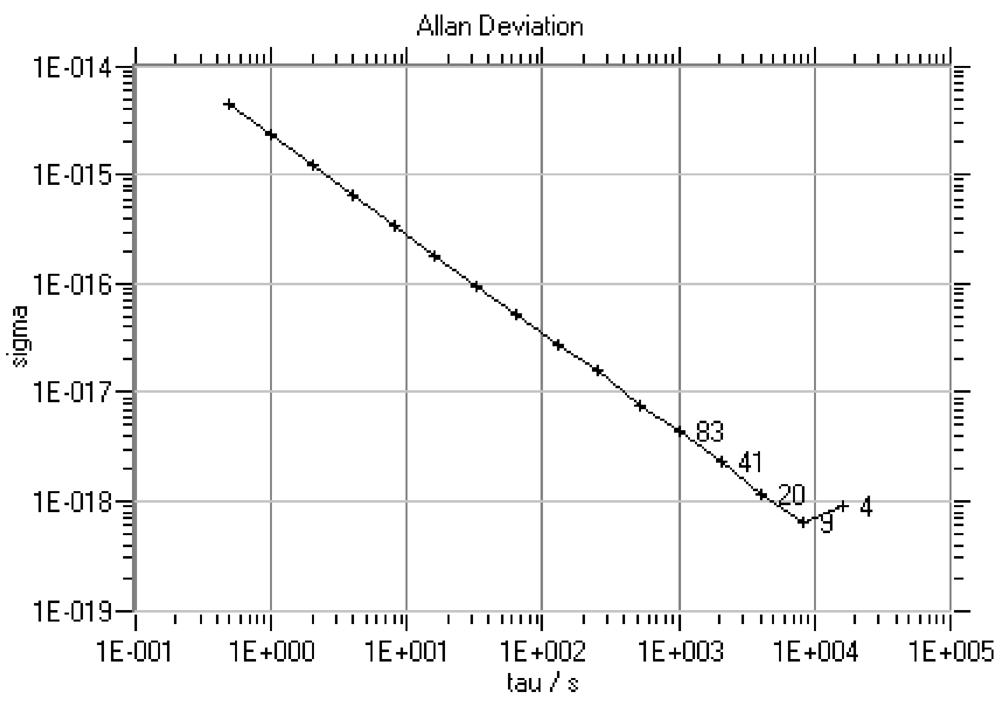

Figure 5. Noise floor of the Frequency Standards Stability Analyzer (FSSA) **[5]**.

In addition to the validation and certification of the frequency standards in operation in the DSN, the FSTL operates five hydrogen masers (inclusive of two spares for the DSN) and one cavity compensated

hydrogen maser. The laboratory also operates two quadrupole Mercury LITS standards **[14]** and a multi-pole LITS standard with exceptional long term stability **[15]**. In 2007, the FSTL has also introduced a Cesium Atomic Fountain, which was adapted and completed from test bed components **[16]** used in a NASA flight program. The FSTL also operates a number of GPS time transfer receivers, and a continuously operating Cryogenic Sapphire Oscillator **[6,7,9]** for state-of-the-art phase noise measurements, atomic frequency standard clean-up applications, or passive frequency standard Local Oscillator (LO) applications.

Stable reference signals from the FSTL frequency standards are distributed around JPL for advanced ground and spacecraft development and testing. Reference signals are currently distributed for DSN array development and the Mars Science Laboratory (MSL), which is in development in preparation for launch in September 2009. In addition to the FSTL being instrumental in operating a state-of-the-art and reliable DSN FTS, its unique capabilities also provide an ideal environment for developing new state-of-the-art frequency standards, distribution, and measurement technology.

2007 DEVELOPMENT HIGHLIGHTS

MULTI-POLE LITS FOR TIMEKEEPING

Linear Ion Trap Standards (LITS) developed over many years at JPL have demonstrated excellent short- and long-term stability and have also demonstrated long-term field operation. Short-term stability of $2\times10^{-14}/\tau^{1/2}$ has been achieved with an atomic line Q of 5×10^{12}, the highest ever demonstrated in a microwave atomic standard operating at room temperature **[14,17,18]**.

The multi-pole LITS **[19]** evolved from its predecessor, the quadrupole LITS, in an effort to improve LITS long-term stability for extreme timekeeping applications. The configuration of the advanced multi-pole LITS has been described in detail elsewhere **[17-21]**. It consists of a conventional quadrupole trap (where ion loading, state selection, and state detection take place) and a multi-pole trap (where the sensitive microwave interrogation takes place). After loading and atomic state selection, ions are "shuttled" into the multi-pole trap by varying the relative trap DC biases. After microwave interrogation, ions are shuttled back to the quadrupole trap for state detection. This configuration not only takes advantage of the reduced second-order Doppler shift in the multi-pole trap, but also separates microwave interrogation from the various perturbations associated with the loading region. Component choices were dictated by the requirement for long-term operation and simplicity. No lasers, cryogenics, or microwave cavities are employed in the design.

Two complete ground-based versions of the multi-pole LITS have been developed, the initial version (LITS-8) operated and evaluated at the USNO **[22]**, and a recently improved version (LITS-9) operated and evaluated at the JPL FSTL **[15,17,18,23]**. Techniques have been developed and applied to LITS-9 to further reduce sensitivity to the second-order Doppler shift by introducing a small magnetic inhomogeneity **[17,23]**. Recent developments have reduced the sensitivity to all residual systematic effects to less than 5×10^{-17}. In the last year, the first long-term comparisons with other highly stable clocks and clock ensembles have been made. Using GPS carrier-phase time transfer over a 9-month period, the compensated multi-pole LITS compared to UTC had a relative frequency difference of $3.3(0.2)\times10^{-17}$/day **[15]**. The long-term stability of LITS-9, a single unsteered frequency standard, as compared to UTC over 6 months of this measurement interval, is shown in Figure 6. Also shown over

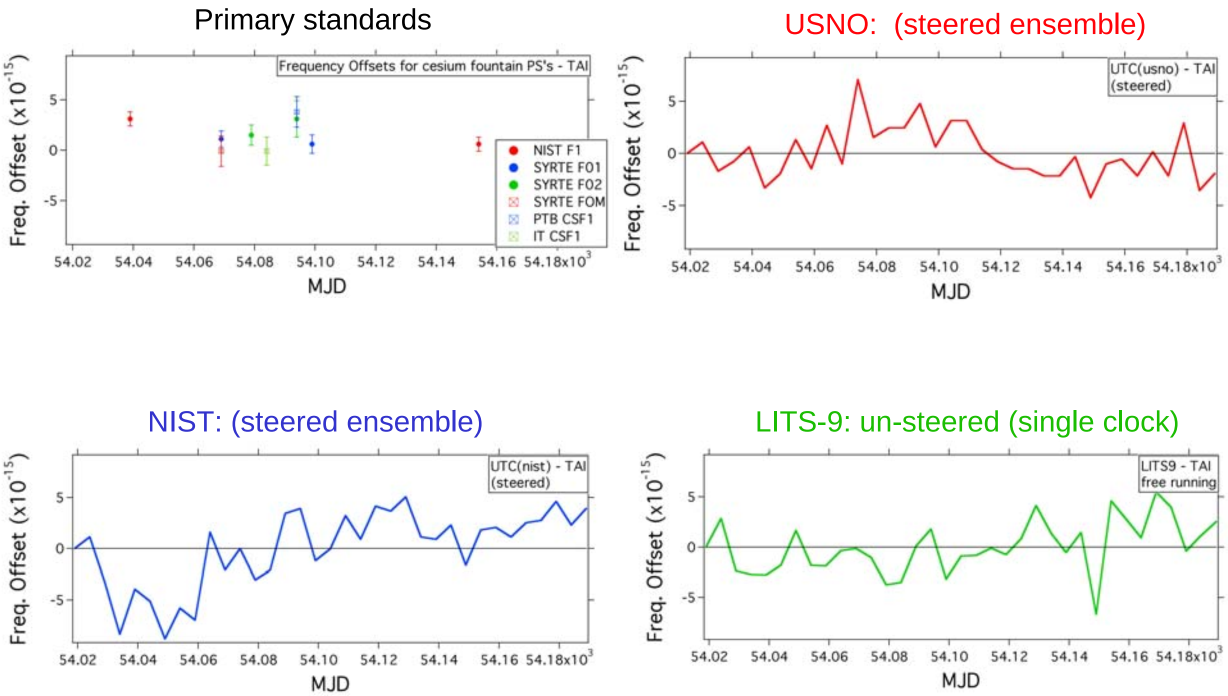

Figure 6. Long-term primary standards, UTC (k) clock ensembles, and LITS stability compared to UTC.

this period is the stability of two of the best UTC (k) clock ensembles which are intentionally steered to UTC. The observed scatter in the primary standard comparisons with respect to UTC suggests that much of the uncertainty in all of these comparisons may be due to time transfer noise limitations.

The systematic sensitivities of the multi-pole LITS are summarized in **[18]**. The largest of these are ion-number-dependent effects, the second-order Zeeman shift, and the pressure shift due to collisions between trapped mercury ions and the background buffer gas. The source of each of these – the number of ions trapped, the average magnetic field in the interrogation region, and the background pressure – remain uncontrolled for simplicity and operational robustness. With the recently introduced magnetic compensation, sensitivities to trapped ion number fluctuations via the second-order Doppler shift are no longer the leading limitation to achieved long-term stability. Collision shifts and the stability of the vacuum environment are now the leading limitation and is an area of active research (see Ref. **[24]**).

A small multi-pole standard is also being developed for possible space flight applications **[25,26]**. A recent laboratory-based breadboard of a small physics package (volume ~2 liters) with a sealed vacuum system has demonstrated fractional stability of 10^{-14} over time intervals of 1,000 seconds or more **[27]**. This size and performance has promise for future space navigation applications. A flight-hardened design of a small physics unit is near completion and is scheduled to be fabricated in 2008 (see Ref. **[28**).

DSN Coherent Reference Generator Replacement

A current effort is underway to replace the critical DSN Coherent Reference Generator (CRG) **[29]**. In Figure 1, the CRG encompasses the central atomic frequency standard selection switching system and

frequency distribution hub to all DSN antennas and frequency and timing users. The burden on this system is extensive as any failure can cause a tracking interruption and operational loss of an entire DSCC. As the system is used for distributing frequency metrology references *and* to support applications requiring excellent differential stability (e.g., for radio science or antenna arraying), the distribution system stability must be significantly more stable than the frequency standard performance summarized in Figure 2.

A system has been developed following many of the principles of the master clock and timing system replacement design **[12,13]**. The CRG replacement system, schematically shown in Figure 7, consists of two new subsystems referred to as the Frequency Reference Selection Assembly (FRS) and the Frequency Reference Distribution Assembly (FRD) **[29]**. The FRS and FRD are modular, sustainable systems and consist of a blend of custom and commercially available components. The FRS is designed to process standard 100 MHz reference signals. A flywheel oscillator has also been introduced to reduce the reliability burden on the more complicated (and generally less reliable) atomic frequency standards and to prevent brief signal dropouts or undesirable phase mismatches when frequency standards are switched. The FRD and FRS subsystems will be implemented into the DSN starting in late 2008.

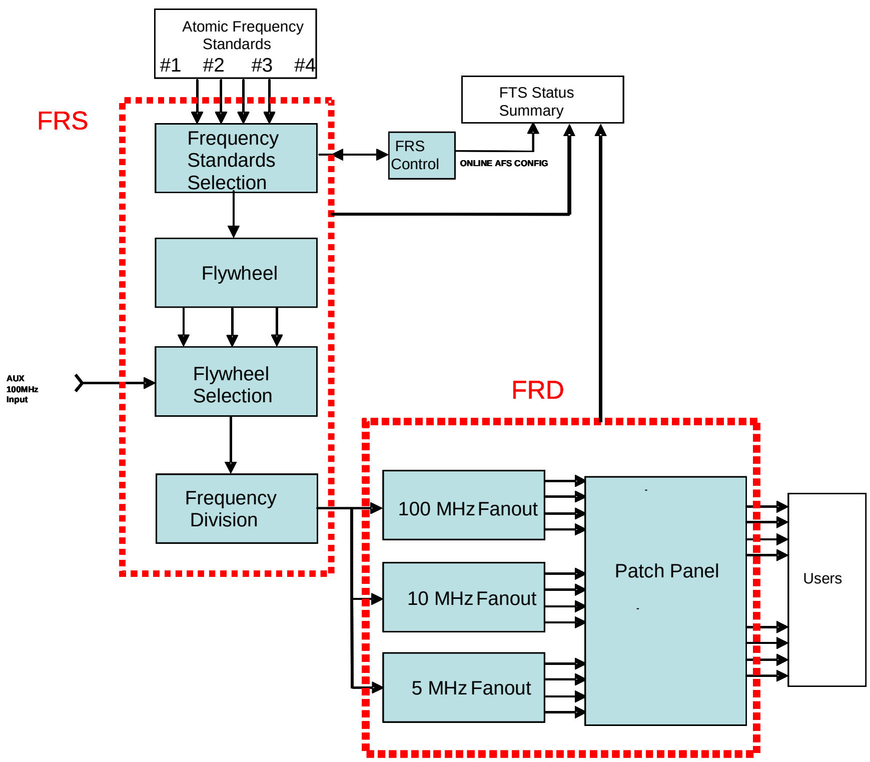

Figure 7. Frequency distribution schematic to replace the DSN Coherent Reference Generator.

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The FRD and FRS subsystems will be implemented into the DSN starting in late 2008.

In the DSN, there is also current activity to extend tracking and navigation capabilities to Ka-band. Present comb generator systems, as represented in Figure 1, derive a stable frequency reference from open-loop fiber-optic-based 100 MHz distribution systems (not shown) and are currently implemented to provide phase-calibration tones at S and X bands. These stable references can be used to calibrate antenna and receiver electronics over time, e.g., over an 8-hour VLBI observation window. Recently, a phase calibration generator at Ka-band has been developed **[30]** and demonstrated at the specialized radio science antenna DSS-25 **[8,9]** at Goldstone, California DSCC. The implementation of this capability is being pursued to support generating an improved Ka-band quasar catalog and reference frame for future DDOR navigation products.

STABILIZED PHOTONIC LINKS & ARRAY APPLICATIONS

For useful application of time and frequency metrology, it is essential that the signal distribution capability not degrade the reference source or transported data. For example, the DSN FTS has several fiber-optic distribution capabilities to transport calibrated and stable atomic frequency standard and clock reference signals to users distributed up to 30 km from the reference source. Currently, both open and closed loop systems are utilized to distribute reference signals to frequency and timing users. For the most demanding DSN applications, long-term phase variations are measured and compensated to very high precision by the Stabilized Fiber Optic Distribution Assembly (SFODA) **[10,11,13]**. This capability transports stable 100 MHz reference and 4 GHz exciter signals from SPC-10 to DSS-25 in support of the Cassini radio science experiments (see, e.g., **[8,9]**). This technology, though, is large and not cost-effective for mass production.

Applications requiring multiple antennas, such as antenna arraying and connected element interferometery, place significant demands on relative and temporal stability of parallel distribution links to or from each antenna. NASA has recently undertaken an ambitious effort to develop an antenna array system with capability to replace the current DSN. A preliminary downlink design envisions ~400 12-meter diameter antennas per DSN site to receive signals at both X- and Ka-band. These applications require excellent time and phase alignment and long-term reference stability for hours to days at the 1-ps level to correlate received signals. This can be accomplished with high-precision phase monitoring or stabilized fiber-optic links that can transport unperturbed RF signals, which may range in frequency from 100 MHz to 40 GHz.

We have recently developed an all-photonic-link approach that combines the benefits of active stabilization with an antenna remoting configuration (i.e., transport of received S-, X-, or Ka-band signals before down-conversion), resulting in a dramatically simplified array signal architecture **[10,32,33]**. A cost-effective, integrated fiber-optic calibration technology provides long-term phase stability in the actual link used for broadband signal transport. Photonic components, such as transmitters, receivers, and modulators with capability up to 1 GHz are very cost-effective and widely available in the telecommunications industry. Photonic components with capability for signal processing at X-band are more expensive, though availability and cost-effectiveness continues to improve. For the proposed DSN

Figure 8. DSN 34-meter antennas linked with high-performance frequency distribution on fiber-optic cables.

array, signals must be transported at X- and Ka-band. Ka-band components are also now becoming commercially available, with markets growing and prices falling. These new design approaches should directly benefit antenna-array downlink applications that require signal phase alignment at a central site in order to correlate received signals. It also provides direct benefit to antenna array uplink applications that require phase alignment of all transmitted signals at the receiving target.

CONCLUSION

JPL time and frequency activities contribute to the overall NASA mission to explore space and are essential for the NASA Deep Space Network. The DSN FTS is highly specialized and must provide state-of-the-art metrology in a distributed remote operational environment that demands very high reliability. This tradeoff has defined many of the past, present, and likely future technology development activities at JPL.

Frequency and timing advances at NASA must continue in support of even more ambitious space mission plans, which include upcoming challenges such as precision landing, formation flying, and autonomous deep space navigation. The NASA Exploration Program is working on a standardized infrastructure for disseminating time information and synchronizing time between assets distributed throughout the solar system. These challenges will drive frequency and timing technologies that are more reliable and lower cost. Appropriate high-performance technologies with favorable size, mass, power, lifetime, and high-operability features are needed.

Technology relying on coherent optical references (not discussed here) is an active topic in ground-based frequency metrology. While these technologies should provide an intriguing path to the future, small ultra-stable microwave technologies have only begun to be exploited for challenging operational environments and extended spaceflight systems.

ACKNOWLEDGMENTS

The successful developments and advancement of the DSN FTS and FSTL could not be accomplished without the efforts of many at JPL. I especially would like to acknowledge the technical excellence and commitment of members of the Frequency and Timing Advanced Instrument and Development Group; Eric Burt, Malcolm Calhoun, Bill Diener, Daphna Enzer, Jorge Gonzalez, Chuck Greenhall, Bob Hamell, Shouhua Huang, Al Kirk, John Lauf, Blake Tucker, and Rabi Wang.

REFERENCES

[1] C. Thorton and J. Border, 2000, *"Radiometric Tracking Techniques for Deep Space Navigation,"* JPL Publications 00-11, Monograph 1, Deep Space Communications & Navigation Series, October 2000.

[2] J. Gonzalez, M. Calhoun, S. Cole, and R. L. Tjoelker, 2001, *"Multi-purpose Time Analyzer and Monitor for Deep Space Network Time Synchronization,"* in Proceedings of the 32nd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 28-30 November 2000, Reston Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 341-354.

[3] C. A. Greenhall, 2000, *"Common-source phase error of a dual-mixer stability analyzer,"* TMO Progress Report, 42-143 (Jet Propulsion Laboratory, Pasadena, California).

[4] C. A. Greenhall, A. Kirk, and G. L. Stevens, 2002, *"A multi-channel dual-mixer stability analyzer: progress report,"* in Proceedings of the 33rd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 27-29 November 2001, Long Beach, California, USA (U.S. Naval Observatory, Washington, D.C., USA), pp. 377-384.

[5] C. Greenhall, A. Kirk, and R. L. Tjoelker, 2007, *"A Multi-Channel Stability Analyzer for Frequency Standards in the Deep Space Network,"* in Proceedings of the 38th Annual Precise Time and Time Interval Meeting (PTTI) Systems and Applications Meeting, 5-7 December 2006, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 105-115.

[6] G. J. Dick and R. T. Wang, 1999, *"Stability and Phase Noise Tests of Two Cryo-cooled Sapphire Oscillators,"* in Proceedings of the 1999 Joint Meeting of the European Frequency and Time Forum (EFTF) and IEEE Frequency Control Symposium, April 1999, Besançon, France (IEEE Publication 99CH36313), pp. 548-551.

[7] G. J. Dick, R. T. Wang, and R.L. Tjoelker, 1998, *"Cryo-Cooled Sapphire Oscillator with Ultra-High Stability,"* in Proceedings of the 1998 IEEE International Frequency Control Symposium, 27-29 May 1998, Pasadena, California, USA (IEEE Publication 98CH36165), pp. 528-533.

[8] M. Calhoun, R. Wang, A. Kirk, W. Diener, G. Dick, and R. Tjoelker, 2001, *"A Stabilized Reference Frequency for Radio Science with the Cassini Spacecraft and the Deep Space Network,"* in Proceedings of the 32nd Annual Precise Time and Time Interval (PTTI) Systems and Applications

Meeting, 28-30 November 2000, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 331-340.

[9] R. T. Wang, M. D. Calhoun, A. Kirk, W. A. Diener, G. J. Dick, and R. L. Tjoelker, 2005, *"A High Performance Frequency Standard and Distribution System for Cassini Ka-Band Experiment,"* in Proceedings of the 2005 Joint IEEE International Frequency Control Symposium and Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 29-31 August 2005, Vancouver, Canada (IEEE Publication 05CH37664C), pp. 919-924.

[10] M. Calhoun, S. Huang, and R. L. Tjoelker, 2007, *"Stable Photonic Links for Frequency and Time Transfer in the Deep-Space Network and Antenna Arrays,"* **Proceedings of the IEEE,** 1931-1946.

[11] M. Calhoun, G. J. Dick, and R. T. Wang, 1999, *"Frequency Transfer and Cleanup System for Ultra High Stability at Both Long and Short Times for Cassini Ka Band Experiment,"* in Proceedings of the 30^{th} Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 1-3 December 1998, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 405-412.

[12] J. Lauf, M. Calhoun, P. F. Kuhnle, R. L. Sydnor, and R. L. Tjoelker, 2004, *"Master Clock and Time Distribution System for the NASA Deep Space Network,"* in Proceedings of the 35^{th} Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 2-4 December 2003, San Diego, California, USA, pp. 371-381.

[13] R. L. Tjoelker, M. Calhoun, P. F. Kuhnle, J. Lauf, and R. L. Sydnor, 2006, *"Master Clock and Time Distribution System for the NASA Deep Space Network: Part I,"* IPN Progress Report 42-167, 15 November 2006.

[14] R. L. Tjoelker, C. Bricker, W. Diener, R. L. Hamell, A. Kirk, P. Kuhnle, L. Maleki, J. D. Prestage, D. Santiago, D. Seidel, D. A. Stowers, R. L. Sydnor, and T. Tucker, 1996, *"A Mercury Ion Frequency Standard Engineering Prototype for the NASA Deep Space Network,"* in Proceedings of the 1996 IEEE Frequency Control Symposium, 5-7 June 1996, Honolulu, Hawaii (IEEE Publication 96CH35935), pp. 1073-1081.

[15] E. A. Burt, W. A. Diener and R. L. Tjoelker, 2007, *"Improvements to JPL's Compensated Multi-Pole Linear Ion Trap Standard and Long-Term Measurements at the 10^{-16} Level,"* in Proceedings of the 2007 Joint Meeting of the European Frequency and Time Forum (EFTF) and the IEEE Frequency Control Symposium (FCS), 29 May-1 June 2007, Geneva, Switzerland, pp. 1041-1049. E. A. Burt, W. A. Diener, and R. L. Tjoelker, *"A Compensated Multi-pole Linear Ion Trap Mercury Frequency Standard for Ultra-Stable Timekeeping,"* submitted to the **IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control.**

[16] D. G. Enzer and W. M. Klipstein, 2004, *"Performance of the PARCS Testbed Cesium Fountain Frequency Standard,"* in Proceedings of the 2004 IEEE International Frequency Control Symposium, 23-27 August 2004, Montreal, Canada (IEEE Publication), pp. 775-779.

[17] E. A. Burt and R. L. Tjoelker, 2005, *"Characterization and Reduction of Number Dependent Sensitivity in Multi-pole Linear Ion Trap Standards,"* in Proceedings of the 2005 Joint IEEE International Frequency Control Symposium and Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 29-31 August 2005, Vancouver, Canada (IEEE Publication 05CH37664C), pp. pp. 466-471.

[18] E. Burt, D. G. Enzer, R. T. Wang, W. A. Diener, and R. L. Tjoelker, 2007, *"Sub-10^{-16} Frequency Stability in the JPL Multi-pole Linear Ion Trap Standard,"* in Proceedings of the 38th Annual Precise Time and Time Interval Meeting (PTTI) Systems and Applications Meeting, 5-7 December 2006, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 271-292.

[19] J. D. Prestage, R. L. Tjoelker, and L. Maleki, 1999, *"Higher Pole Linear Traps for Atomic Clock Applications,"* in Proceedings of the 1999 Joint Meeting of the European Frequency and Time Forum (EFTF) and the IEEE International Frequency and Time Forum (FCS), 13-16 April 1999, Becançon, France (IEEE Publication 99CH36313), pp. 121-124.

[20] R. L. Tjoelker, J. D. Prestage, and L. Maleki, 2000, *"Improved Timekeeping Using Advanced Trapped-Ion Clocks,"* in Proceedings of the 31st Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 7-9 December 1999, Long Beach, California, USA (U.S. Naval Observatory, Washington, D.C.), pp. 597-604.

[21] J. D. Prestage, R. L. Tjoelker, and L. Maleki, 2000, *"Mercury-Ion Clock Based on Linear Multi-pole Ion Trap,"* in Proceedings of the 2000 International Frequency Control Symposium, 7-9 June 2000, Kansas City, Missouri (IEEE Publication 00CH37052), pp. 706-710.

[22] R. L.Tjoelker, J. D. Prestage, P. A. Koppang, and T. B. Swanson, 2003, *"Stability Measurements of a JPL Multi-pole Mercury Trapped Ion Frequency Standard at the USNO,"* in Proceedings of the 2003 IEEE International Frequency Control Symposium (FCS) & PDA Exhibition Jointly with the 17th European Frequency and Time Forum (EFTF), 4-8 May 2003, Tampa, Florida, USA (IEEE Publication 03CH37409), pp. 1066-1072.

[23] E. A. Burt, J. D. Prestage, and R. L. Tjoelker, *"Probing Magnetic Field Effects in 12-Pole Linear Ion Trap Frequency Standards,"* in Proceedings of the 2002 IEEE International Frequency Control Symposium, 29-31 May 2002, New Orleans, Louisiana, USA (IEEE Publication 02CH37234), pp. 463-468.

[24] E. Burt and R. L. Tjoelker, 2008, *"Prospects for Ultra-Stable Timekeeping with Sealed Vacuum Operation in Multi-pole Linear Ion Trap Standards,"* in Proceedings of the 39th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 26-29 November 2007, Long Beach, California, USA (U.S. Naval Observatory, Washington, D.C.), pp. 309-316.

[25] R. L. Tjoelker, E. Burt, S. Chung, R. Glaser, R. Hamell, L. Lim, L. Maleki, J. D. Prestage, N. Raouf, T. Radey, C. Sepulveda, G. Sprague, B. Tucker, and B. Young, 2002, *"Mercury Trapped-Ion Frequency Standard for the Global Positioning System,"* in Proceedings of the 33rd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 27-29 November 2001, Long Beach, California, USA (U.S. Naval Observatory, Washington, D.C.), pp. 45-54.

[26] J .D. Prestage, S. Chung, T. Le, M. Beach, L. Maleki, and R. L. Tjoelker, 2004, *"One-Liter Ion Clock: New Capability for Spaceflight Applications,"* in Proceedings of the 35th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 2-4 December 2003, San Diego, California, USA (U.S. Naval Observatory, Washington, D.C.), pp. 427-433.

[27] J. D. Prestage, S. Chung, L. Lim, and A. Matevosian, 2007, *"Compact Microwave Mercury Ion Clock for Deep Space Applications,"* in 21st European Frequency and Time Forum (EFTF) Joint with

2007 IEEE International Frequency Control Symposium (IEEE-FCS), 29 May-1 June 2007, Geneva, Switzerland (IEEE Publication CH37839), pp. 1113-1115.

[28] J. D. Prestage, S. Chung, L. Lim, T. Le, and M. Tu, 2008, *"10-15 Stable Ion Clock for Deep Space and Earth Orbit Applications,"* in Proceedings of the 39th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 26-29 November 2007, Long Beach, California, USA (U.S. Naval Observatory, Washington, D.C.), pp. 249-256.

[29] B. Tucker, W. Diener, J. Gonzalez, R. Hamell, J. Lauf, and R.L. Tjoelker, to be published in NASA IPN Progress Reports (Jet Propulsion Laboratory, Pasadena, California).

[30] B. Tucker, to be published in NASA IPN Progress Reports (Jet Propulsion Laboratory, Pasadena, California).

[31] M. Calhoun, R. Sydnor, and W. Diener, 2002, *"A Stabilized 100 MHz and 1 GHz Reference Frequency Distribution for Cassini Radio Science,"* IPN Progress Report 42-147 (Jet Propulsion Laboratory, Pasadena, California), February 2002.

[32] S. Huang and R L. Tjoelker, 2007, *"Stabilized Photonic Link for Frequency and Time Transfer in Antenna Arrays,"* in Proceedings of the 38th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 5-7 December 2006, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 293-303.

[33] S. Huang and R.L. Tjoelker, 2006, *"All Photonic Link for High Performance Antenna Arraying,"* IPN Progress Report 42-167 (Jet Propulsion Laboratory, Pasadena, California), 15 November 2006.